FORM PTO-1390 US DEPARTMENT OF COMMERCE REV. 5-93 PATENT AND TRADEMARK OFFICE **TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371**	ATTORNEYS DOCKET NUMBER **P99,0101** U.S.APPLICATION NO. (if known, see 37 CFR 1.5) 09/367778

INTERNATIONAL APPLICATION NO. **PCT/DE98/00633**	INTERNATIONAL FILING DATE **03 MARCH 1998**	PRIORITY DATE CLAIMED **11 MARCH 1997**

TITLE OF INVENTION
METHOD FOR COMPUTER-SUPPORTED ERROR ANALYSIS OF SENSORS AND/OR ACTUATORS IN A TECHNICAL SYSTEM

APPLICANT(S) FOR DO/EO/US
PETER LIGGESMEYER

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. ☒ This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. ☒ This express request to begin national examination procedures (35 U.S.C. 371(f)) at any time rather than delay.
4. ☒ A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date.

5. ☒ A copy of International Application as filed (35 U.S.C. 371(c)(2)) - drawings attached.
   a. ☒ is transmitted herewith (required only if not transmitted by the International Bureau).
   b. ☐ has been transmitted by the International Bureau.
   c. ☐ is not required, as the application was filed in the United States Receiving Office (RO/US)
6. ☒ A translation of the International Application into English (35 U.S.C. 371(c)(2) - drawings attached.

7. ☐ Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. §371(c)(3))
   a. ☐ are transmitted herewith (required only if not transmitted by the International Bureau).
   b. ☐ have been transmitted by the International Bureau.
   c. ☐ have not been made; however, the time limit for making such amendments has NOT expired.
   d. ☐ have not been made and will not be made.

8. ☐ A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).

9. ☒ An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)).

10. ☐ A translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).

Items 11. to 16. below concern other document(s) or information included:

11. ☒ An Information Disclosure Statement under 37 C.F.R. 1.97 and 1.98; **(PTO 1449, Prior Art, Search Report).**

12. ☒ An assignment document for recording. A separate cover sheet in compliance with 37 C.F.R. 3.28 and 3.31 is included. **(SEE ATTACHED ENVELOPE)**

13. ☒ A FIRST preliminary amendment.
    ☐ A SECOND or SUBSEQUENT preliminary amendment.

14. ☐ A substitute specification.

15. ☐ A change of power of attorney and/or address letter.

16. ☒ Other items or information:
    a. ☒ Submission of Drawings - 9 sheets of drawings, Figures 1-9.

    b. ☒ EXPRESS MAIL #EL345371101US dated August 18, 1999.

U.S. APPLICATION NO (if known, see 37 C.F.R. 1.5) 09/367778	INTERNATIONAL APPLICATION NO **PCT/DE98/00633**	ATTORNEY'S DOCKET NUMBER **P99,0101**

17. ☒ The following fees are submitted: **BASIC NATIONAL FEE (37 C.F.R. 1.492(a)(1)-(5):** Search Report has been prepared by the EPO or JPO . . . . $840.00 International preliminary examination fee paid to USPTO (37 C.F.R. 1.482) $670.00 No international preliminary examination fee paid to USPTO (37 C.F.R. 1.482) but international search fee paid to USPTO (37 C.F.R. 1.445(a)(2) . . . . $760.00 Neither international preliminary examination fee (37 C.F.R. 1.482) nor international search fee (37 C.F.R. 1.445(a)(2) paid to USPTO . . . . $970.00 International preliminary examination fee paid to USPTO (37 C.F.R. 1.482) and all claims satisfied provisions of PCT Article 33(2)-(4) . . . . $ 96.00	CALCULATIONS	PTO USE ONLY
ENTER APPROPRIATE BASIC FEE AMOUNT =	$ 840.00	
Surcharge of $130.00 for furnishing the oath or declaration later than □ 20 □ 30 months from the earliest claimed priority date (37 C.F.R. 1.492(e)).	$	

Claims	Number Filed	Number Extra	Rate		
Total Claims	11 - 20 =	0	X $ 18.00	$	
Independent Claims	05 - 3 =	2	X $ 78.00	$ 156.00	
Multiple Dependent Claims			$260.00 +	$	
TOTAL OF ABOVE CALCULATIONS =				$ 996.00	
Reduction by ½ for filing by small entity, if applicable. Verified Small Entity statement must also be filed. (Note 37 C.F.R. 1.9, 1.27, 1.28)				$	
SUBTOTAL =				$ 996.00	
Processing fee of $130.00 for furnishing the English translation later than □ 20 □ 30 months from the earliest claimed priority date (37 CFR 1.492(f)). +				$	
TOTAL NATIONAL FEE =				$ 996.00	
Fee for recording the enclosed assignment (37 C.F.R. 1.21(h). The assignment must be accompanied by an appropriate cover sheet (37 C.F.R. 3.28, 3.31). $40.00 per property +					
TOTAL FEES ENCLOSED =				$ 996.00	
				Amount to be refunded	$
				charged	$

a. ☒ A check in the amount of $ 996.00 to cover the above fees is enclosed.

b. □ Please charge my Deposit Account No. ____________ in the amount of $ ________ to cover the above fees. A duplicate copy of this sheet is enclosed.

c. ☒ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. 08-2290. A duplicate copy of this sheet is enclosed.

NOTE: Where an appropriate time limit under 37 C.F.R. 1.494 or 1.495 has not been met, a petition to revive (37 C.F.R. 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

SEND ALL CORRESPONDENCE TO:

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IN THE UNITED STATES ELECTED OFFICE
OF THE UNITED STATES PATENT AND TRADEMARK OFFICE
UNDER THE PATENT COOPERATION TREATY-CHAPTER II

PRELIMINARY AMENDMENT

APPLICANT: Peter Liggesmeyer DOCKET NO: P99,0101
SERIAL NO: GROUP ART UNIT:
EXAMINER:
INTERNATIONAL APPLICATION NO: PCT/DE98/00633
INTERNATIONAL FILING DATE: 03 MARCH 1998
INVENTION: **METHOD FOR COMPUTER-SUPPORTED ERROR ANALYSIS OF SENSORS AND/OR ACTUATORS IN A TECHNICAL SYSTEM**

Assistant Commissioner for Patents,
Washington, D.C. 20231

Sir:

Please amend the above-identified application as follows before calculation of the U.S. national fee under 35 U.S.C. 371 (c) (1).

IN THE SPECIFICATION:

On page 1, please delete lines 1-4 and insert the following:

--SPECIFICATION

TITLE

METHOD FOR COMPUTER-SUPPORTED ERROR ANALYSIS OF SENSORS AND/OR ACTUATORS IN A TECHNICAL SYSTEM

BACKGROUND OF THE INVENTION--.

On page 1, line 11, please change "[1]" to --DIN 25424, Part 1: Fehlerbaumanalyse: Methode und Bildzeichen; Part 2: Handrechenverfahren zur Auswertung eines Fehlerebaums--.

On page 1, line 12, please change "[2]" to --J. Dekleer and B. C. Williams, Diagnosing Multiple Faults, , Elsevier Science Publishers, Artificial Intelligence, Vol. 32, 1987, pp. 97-130--.

On page 1, line 20, please change "[2]" to --the Dekleer et al reference--.

On page 1, line 24, please change "[2]" to --the Dekleer et al reference--.

On page 2, line 12, please change "[3]" to --K. Nökel, K. Winkelmann, Controller Synthesis and Verification: A Case Study, in: C. Leverentz, T. Lindner, Formal Development of Reactive Systems, Lecture Notes in Computer Science (No. 891), Springer 1995, pp. 55-74--.

On page 2, line 18, please change "[4]" to --J. Burch et al, Symbolic Model Checking for Sequential Circuit Verification, IEEE Trans. On Computer-Aided Design of Integrated Circuits and Systems, Vol. 13, No. 4, pp. 401-424, April 1994--.

On page 2, line 21, please change "[5]" to --R. Bryant, Symbolic Boolean Manipulation with Ordered Binary-Decision Diagrams, ACM Computing Survey, Vol. 24, No. 3, pp. 293-318, September 1992--.

On page 2, after line 23, as a separate line before line 24, please insert the following heading:

--**SUMMARY OF THE INVENTION**--.

On page 2, please delete lines 27-28.

On page 2, line 29, after "method" please insert --according to the present invention--.

On page 3, please delete lines 22-23.

On page 4, please delete lines 15-17 and insert the following heading and paragraph:

--**<u>BRIEF DESCRIPTION OF THE DRAWINGS</u>**

The features of the present invention which are believed to be novel, are set forth with particularity in the appended claims. The invention, together with further objects and advantages, may best be understood by reference to the following description taken in conjunction with the accompanying drawings, in the several Figures of which like reference numerals identify like elements, and in which:--.

On page 4:

line 18, after "Figure 1" please insert --is--;

line 19, after "Figure 2" please insert --is--;

line 23, after "Figure 3" please insert --is--;

line 26, after "Figure 4" please insert --is--;

line 28, after "Figure 5" please insert --is--.

On page 5:

line 1, after "Figure 6" please insert --is--;

line 3, after "Figure 7" please insert --is--;

line 5, after "Figure 8" please insert --is--;

line 6, after "Figure 9" please insert --is--.

On page 5, after line 7, as a separate line before line 8, please insert the following heading:

--**<u>DESCRIPTION OF THE PREFERRED EMBODIMENTS</u>**--.

On page 7, line 17, please change "[4]" to --J. Burch et al, Symbolic Model Checking for Sequential Circuit Verification, IEEE Trans. On Computer-Aided Design of Integrated Circuits and Systems, Vol. 13, No. 4, pp. 401-424, April 1994--.

On page 11, line 30, please change “implement” to --use--.

On page 12, line 13, please change “[5]” to --R. Bryant, Symbolic Boolean Manipulation with Ordered Binary-Decision Diagrams, ACM Computing Survey, Vol. 24, No. 3, pp. 293-318, September 1992--.

On page 15, line 13, please change “in error [...]” to --for the occurrence of error--.

On page 15, line 14, please change “[1]” to --DIN 25424, Part 1: Fehlerbaumanalyse: Methode und Bildzeichen; Part 2: Handrechenverfahren zur Auswertung eines Fehlerebaums--.

On page 15, after line 18, please insert the following paragraph:

--The invention is not limited to the particular details of the method and apparatus depicted and other modifications and applications are contemplated. Certain other changes may be made in the above described method and apparatus without departing from the true spirit and scope of the invention herein involved. It is intended, therefore, that the subject matter in the above depiction shall be interpreted as illustrative and not in a limiting sense.--.

IN THE CLAIMS:

On page 16, line 1, please change “**PATENT CLAIMS**” to --**WHAT IS CLAIMED IS:**--

Please amend claims 1-11 as follows:

1. **(Amended)** [Method] A method for computer-supported error analysis of at least one of sensors [and/or] and actuators in a technical system [that is present in the], the error analysis being in a form of a status-finite description that exhibits statuses of the technical system, the method using a computer[.], comprising the steps of:

a) determining [whereby] a status-finite description of the technical system [is determined] for [the] an error case [for] of an error of at least one of a sensor [and/or of] and an actuator in the technical system;

b) determining [whereby] a first set of achievable statuses [is determined] for the technical system;

c) determining [whereby] a second set of achievable statuses [is determined] for the [error-effected] technical system having an error;

d) forming [whereby] a difference set [is formed] from the first set and the second set; and

e) determining [whereby] result conditions [are determined] from the difference set, [these] the result conditions meeting prescribable conditions.

2. **(Amended)** [Method] The method according to claim 1, [whereby] wherein method steps a) through f) are implemented for all possible errors of sensors and/or actuators [that] is the technical system [comprises].

3. **(Amended)** [Method] The method according to claim 1 [or 2, whereby] wherein failure probabilities are allocated to the sensors and/or actuators; and [whereby] wherein the error analysis ensues taking the failure probabilities into consideration.

4. **(Amended)** [Method] The method according to claim 1, wherein [one of the claims 1 through 3, whereby] method steps b) and c) [ensues] ensue according to [the] a method of model checking.

5. **(Amended)** [Method] The method according to claim 1, wherein [one of the claims 1 through 4, whereby] a status-finite description of a process implemented by the technical system is [taken into consideration] included in the method.

6. **(Amended)** [Method] The method according to claim 1, wherein [one of the claims 1 through 5, whereby] the status-finite description is realized by a finite automat.

7. **(Amended)** [Method] The method according to claim 6, [whereby] wherein the status-finite is realized by a finite automat in [the] a form of a binary decision diagram [(BDD)].

8. **(Amended)** A method for [Employment of the method according to one of the claims 1 through 7 in] rapid prototyping of [the] a technical system[.], the system having at least one of sensors and actuators in a technical system, the prototyping being in a form of a status-finite description that exhibits statuses of the technical system, the method using a computer, comprising the steps of:

a) determining a status-finite description of the technical system for an error case of an error of at least one of a sensor and an actuator in the technical system;

b) determining a first set of achievable statuses for the technical system;

c) determining a second set of achievable statuses for the technical system having an error;

d) forming a difference set from the first set and the second set; and

e) determining result conditions from the difference set, the result conditions effecting prototyping of the technical system.

9. **(Amended)** A method for [Employment of the method according to one of the claims 1 through 7 in the framework of] error diagnosis of [the] a technical system[.], the system having at least one of sensors and actuators in a technical system, the error diagnosis being in a form of a status-finite description that exhibits statuses of the technical system, the method using a computer, comprising the steps of:

a) determining a status-finite description of the technical system for an error case of an error of at least one of a sensor and an actuator in the technical system;

b) determining a first set of achievable statuses for the technical system;

c) determining a second set of achievable statuses for the technical system having an error;

d) forming a difference set from the first set and the second set; and

e) determining result conditions from the difference set, the result conditions effecting error diagnosis of the technical system.

10. **(Amended)** A method [Employment of the method according to one of the claims 1 through 7] for generating critical test cases for a commissioning and a system test of [the] a technical system[.], the system having at least one of sensors and actuators in a technical system, the generating being in a form of a status-finite description that exhibits statuses of the technical system, the method using a computer, comprising the steps of:

a) determining a status-finite description of the technical system for an error case of an error of at least one of a sensor and an actuator in the technical system;

b) determining a first set of achievable statuses for the technical system;

c) determining a second set of achievable statuses for the technical system having an error;

d) forming a difference set from the first set and the second set; and

e) determining result conditions from the difference set, the result conditions effecting the generation of critical test cases.

11. **(Amended)** A method [Employment of the method according to one of the claims 1 through 7] for preventive maintenance of [the] a technical system[.], the system having at least one of sensors and actuators in a technical system, the method being in a form of a status-finite description that exhibits statuses of the technical system, the method using a computer, comprising the steps of:

a) determining a status-finite description of the technical system for an error case of an error of at least one of a sensor and an actuator in the technical system;

b) determining a first set of achievable statuses for the technical system;

c) determining a second set of achievable statuses for the technical system having an error;

d) forming a difference set from the first set and the second set; and

e) determining result conditions from the difference set, the result conditions effecting the preventive maintenance.

IN THE ABSTRACT

On page 18, please delete lines 1-3, and insert the following heading: --**ABSTRACT OF THE DISCLOSURE**--.

REMARKS

The claims have been amended to place them in proper U.S. form. No new matter is added by the foregoing amendments.

Applicant respectfully requests entry of the above preliminary amendments prior to calculation of the filing fees.

Respectfully submitted,

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SPECIFICATION

METHOD FOR COMPUTER-SUPPORTED ERROR ANALYSIS OF SENSORS AND/OR ACTUATORS IN A TECHNICAL SYSTEM

It is of enormous significance for complex technical systems or installations to be able to make statements about the dependability of the respective system or, respectively, of the installation.

It is known that statements about the dependability of an arbitrary technical system or, respectively, of an installation can be produced manually, for example by what is referred to as an error tree analysis (see [1]) or simulatively or, respectively, analytically on the basis of models specifically produced for this purpose (see [2]). For the sake of a simple presentation, only technical systems shall be mentioned below. However, technical installations are also covered in the term of technical system within the scope of this document. A complete manual determination of the influences of a technical malfunction of sensors and/or actuators is practically not possible in a complex technical system due to the linked dependencies and the different forms of realizing the control, the control system and the sensor mechanisms and/or actuator mechanisms. The analytical techniques disclosed in [2] require the production of a specific model, for which it can generally not be guaranteed that it correctly describes the system respectively under consideration. Of course, the quality of the statements is there substantially reduced. Further, a considerable disadvantage of the approaches disclosed in [2] is that the production of the model requires additional developing outlay and time. As a result thereof, a short-term investigation of alternative realizations of a technical system, which is also referred to as rapid prototyping, is prevented.

It is known to describe a technical system in a status-finite description, for example as automat. A status-finite description usually comprises statuses in which actions are implemented when the technical system is in the respective status. Further, the status-finite description usually comprises status transitions that describe possible changes of the technical system between statuses. The technical system can also implement actions in status transitions. It is known in this context in a controlled, technical system to fashion the status-finite description such that the behavior of the control of the technical system and the behavior of the controlled installation is presented as status automat. It is also not assured given these approaches that all possible influences of errors on the system are correctly identified.

Possibilities for textual description of a status automat that are processed with a computer are, for example, interlocking specification language (ISL) or control specification language (CSL), which are described in [3].

It is also known to employ a status-finite description for generating controls with a computer and for the computer-supported documentation of properties of an error-free technical system.

One possibility for computer-supported documentation of properties of an error-free technical system employs the principle of what is referred to as model checking, this being described in [4].

It is also known for status-finite description of a system to employ what is referred to as a finite state machine format (FSM Format) whose fundamentals are described in [5]. Binary decision diagrams (BDD) have the advantage of also compactly representing very extensive status systems in many instances.

The invention is thus based on the problem of specifying a method for computer-supported error analysis of sensors and/or actuators in a technical system with which the correctness of the error analysis is assured.

This problem is solved by the method comprising the features of patent claim 1.

The method is implemented with a computer and comprises the following steps:

a) a status-finite description of the technical system is determined in case of error for an error of a sensor and/or of an actuator of the system;
b) a first set of achievable conditions is determined for the technical system;
c) a second set of achievable conditions is determined for the error-effected technical system;
d) a difference quantity is formed from the first set and from the second set;
e) result statuses are determined from the difference quantity, these result statuses satisfying prescribable conditions.

The invention can be graphically described in that a model checking is implemented both for the error-free technical system as well as for a system effected with an error of a sensor and/or actuator. Due to the model checking, all achievable conditions of the error-free or, respectively, of the error-effected system are identified. A difference quantity of statuses is formed from these statuses. The statuses of the difference quantity that meet a prescribable condition, for example a safety demand made of the system, are identified for the difference quantity. These statuses represent a "dangerous" condition with respect to the prescribable condition for the error respectively being investigated.

The method assures that all "dangerous" statuses are identified for all conditions prescribable in view of the respectively investigated error, i.e. for the faulty sensor and/or actuator.

Advantageous developments of the invention derive from the dependent claims.

It is advantageous to implement the method for all possible errors of sensors and/or actuators that the technical system comprises. In this way, it is assured for the entire system that all "dangerous" statuses in view of prescribable conditions are identified.

It is also advantageous to allocate failure probabilities to the sensors and/or actuators and to implement the error analysis taking the failure probabilities into consideration. In this way, it is possible without greater calculating outlay in the implementation of the method with a computer to indicate for the identified statuses what the probability is that this status will in fact be reached, a risk estimate for the respectively analyzed system thus becoming extremely simple and surveyable.

For further savings in calculating time in the implementation of the method with a computer, it is also advantageous to realize the status-finite description with a finite automat in the form of a binary decision diagram (BDD).

The method, due to the above-described properties, can be very advantageously employed in the following fields:

- given rapid prototyping of the technical system;
- within the framework of the error diagnosis of the technical system;
- for generating critical test cases for a commissioning and for a system test of the technical system;
- for preventative maintenance of the technical system.

An exemplary embodiment of the invention is shown in the Figures, this being explained in greater detail below.

Shown are:

Figure 1	a sketch-like presentation of the method;
Figure 2	a sketch of a status-finite description of a control and of the process of a technical system controlled by the control, whereby the error-free control and the process are each respectively described as a separate status automat;
Figure 3	a sketch of the status-finite description of Figure 1 with a symbolically illustrated, general sensor error model and actuator error model;
Figure 4	a sketch of the status-finite description from Figure 1 with a symbolically presented, non-persistent error of a sensor;
Figure 5	a sketch of the status-finite description from Figure 1 with the error from Figure 4, whereby the control was modified as replacement of the error model;

Figure 6 a sketch of a plan view of the exemplary embodiment, a lift-off turn table of a manufacturing cell;

Figure 7 a sketch in which the provided movement of the lift-off turntable from Figure 6 is shown;

Figure 8 a sketch of the status space of the error-free lift-off turntables;

Figure 9 a sketch of the status space of an error-effected lift-off turntable.

A suitable status-finite description represents the behavior of the control and the behavior of the control system as status automat. The presentation can ensue in various ways, for example in textual form upon employment of ISL or CSL.

Figure 2 shows a simple technical system with an error-free control FS, statuses y1, y2, y3 and status transitions x1, x2 as status automat. The control S describes actuators as statuses. A controlled process P contains the description of sensors x1, x2, x3 as statuses x1, x2, x3 and status transitions y1, y2, y3.

The control S of the system reacts to measured values xj (x1, x2, x3) of sensors X. Status transitions are therefore thus triggered in the control S by sensor data. The statuses are characterized by values yi (y1, y2, y3) of status variables Y that are allocated to actuators. The setting of actuators Y in turn triggers status transitions in the controlled system, i.e. in the process P, which is expressed in the modification of the values of the sensors X.

The status automats of the control S and of the process P implements status transitions in alternation. The outputs of the one automat are the inputs of the respectively other automat.

The interface between control and controlled environment can be automatically recognized in a corresponding description. Further, it is possible - as described in detail later - to derive the value set from such a description that the individual values (statuses or, respectively, status transitions) can assume.

Figure 3 symbolically shows an error modeling for error-effected sensors in a sensor error model SF and for error-effected actuators in an actuator error model AF.

Technically, thus, sensors X and actuators Y are connected to the interface between control S and controlled process P. A malfunction of a sensor X leads to the fact that a different, error-effected value x'j is delivered to the control S, i.e. supplied to the control S, instead of the correct measured values xj. A malfunction of an actuator is expressed in the setting of an incorrect value y'i instead of the value yi. Which sensors X and actuators Y are present and what value set is to be taken into consideration here can be derived from the status-finite description.

This allows the automated, systematic analysis of the effects of sensor and actuator errors on the behavior of a controlled system. Sensor error models SF or, respectively, actuator error models AF that describe the respective error of the sensor x and/or actuator y are inserted between the controlled process P and the control S. Exemplary models for intermittent (non-persistent), individual errors of the sensor mechanism and actuator mechanism are recited in Figure 3.

A non-persistent, individual error of a sensor x is described by the following rule:

x'j = xj | j ≠ n (error-free values)

(error-effected value).

A non-persistent, individual actuator y is described by the following rule:

(error-free values)

(error-effected value).

Figure 4 shows the general sensor error model SF from Figure 3 for the case that a non-persistent, individual error given a first sensor value x1 is present such that the first sensor value x1 either exhibits the correct, first sensor value x1 or, due to a sensor error, exhibits a second sensor value x2 that would be an incorrect value in this case. The second sensor value x2 and a third sensor value x3 are correctly measured.

An important question that must be answered is whether the combination of control S and control process P can proceed into critical conditions due to the sensor error that would be reliably precluded in the error-free case.

One possibility of producing this proof for the error-free case is offered by what is referred to as model checking, this being described in [4]. This method allows the set of achievable statuses to be identified and to examine whether statuses that, for example, infringe safety conditions are contained.

In order to be able to apply this technique for error analysis of sensors X and/or actuators Y contained in the system, the sensor error models SF or, respectively, actuator error model AF are described here by a modified control logic (see Figure 5).

The combination of control S and controlled process P shown in Figure 5 behaves identically to the model shown in Figure 4 in the error case given the first sensor values x1. However, the insertion of an explicit error model between control S and controlled process P can be foregone here. Due to the assumed, intermittent error, status transitions indicated with x1 are inserted in the control parallel to the status transitions marked with x2.

The following situation is thus described:

the second sensor value x2 and the third sensor value x3 are correctly measured. The controlled behavior is therefore unmodified for these values. Since an intermittent error is assumed, the first sensor value x1 can also be correctly reported, so that these status transitions are maintained. If a persistent exchange of the first sensor value x1 with the second sensor value x2 were assumed, then edges labeled with x1 would have to be erased. All status transitions that are marked with x2 can now also be run at the value x1. A corresponding edge is therefore supplemented in the control S. The control S reacts to the value x2 but at the location x1 of the process.

This modification of the control logic for describing errors can be formally automatically implemented by the computer for all errors that can be considered.

The questions about obtainability of critical conditions (for example safety, seizures) for the arising models can likewise be answered by applying model checking. An automatic determination of the statuses achievable in the error-effected system thus preferably ensues upon application of model checking.

Subsequently, a respected difference set of the statuses achievable in the respective error case and the statuses achievable in the error-free case is determined.

Those statuses that at least meet a condition prescribable by the user (for example, violation of a safety demand) or, respectively, that violate this condition are determined dependent on the application.

The lift-off turntable HD dare never assume a different horizontal position then x0 (left stop) in combination with the vertical position x0 (bottom) since it would otherwise collide with the delivering conveyor belt FB (forbidden area VB).

A description of the status automat of the control FS of the lift-off turntable HD in CSL is recited below:

```
CSLxtClasses table
        Types
         bool                = [no, yes];
         posType             = [x0, x1, x2];
         movType             = [stop, plus, minus];

Class pcd

StateVariables
        input    vpos                : posType default x0;
        input  hpos                  : posType default x0;
        input  part__on__table       : bool      default no;
        output vmov: movType default stop;
        output hmov: movType default stop;

Transitions
start__up       :=      (part__on__table = yes / \ vpos = x0)
                ==>    (** vmov = plus);
rotate          :=      (part__on__table = yes / \ vpos = x1 / \ hpos < x2)
                ==>     (** hmov = plus);
stophigh        :=      (part__on__table = yes / \ vpos = x2)
                ==>     (** vmov = stop);
stop 45         :=      (part__on__table = yes / \ hpos = x2)
                ==>     (** hmov = stop);
rotate_back             := (part__on__table = no / \ vpos = x2 / \
                / \ hpos = x2) ==> (** hmov = minus);
start_down           := (part__on__table = no / \ hpos = x0 / \
                / \ vpos = x2) ==> (** hmov = stop / \
                / \ ** vmov = minus);
stoplow         := (part__on__table = no / \ vpos = x0)
                ==> (** vmov = stop);

End /* Class pcd_control*/
End table
CSLInstances i
        table : pcd;
End i
```

The control logic of the lift-off turntable HD determines the above description in CSL. The head of the CSL description declares data types (value ranges) of the status variables. The subsequent declaration of the status variables uses these type declarations and additionally determines starting values. On the basis of the declaration of status variables as input or output, a determination can be made as to whether it is a matter of a status variable that represents the process condition or whether it encodes the statuses control FS. Input variables of the control FS encode process conditions. Output variables of the control FS encode control conditions. The line “input vpos: posType default x0" declares a status variable having the name “vpos” that can assume the values x0, x1 *and* x2 (the values of the type posType) and whose initial values is x0.

The transitions serve for describing the control logic. Transitions are triggered by value combinations of the input variables of the control FS that represent process conditions - i.e. the position of the lift-off turntable HD in the vertical (vpos) and the horizontal (hpos) motion direction and the presence of a workpiece WS on the lift-off turntable HD (part__on__table). The values of the output variables vmov and hmov are modified by the transitions that implement the control logic. They describe the statuses of the control. Their values are modified only by status transitions of the control, i.e. by the logic impressed on the control.

These information can be automatically taken from the CSL description. A distinction can be made between inputs of the control (inputs, sensor data) and outputs of the control (outputs: actuator commands). Moreover, the respectively possible values can be recognized (type declarations).

Even after the translation of the CSL description in what is referred to as the Finite State Machine format (FSM format), the information are essentially preserved. This FSM format represents the status-finite description in the form of what are referred to as binary decision diagrams (BDD) that have the advantage of also representing very extensive status systems in compact form in many instances [5] presents an overview of binary decision diagrams (BDD).

A process model for describing the reactions of the controlled process is required in addition to the control logic described in CSL in order, for example, to enable statements about the set of achievable statuses. This can ensue in the framework of model checking with the assistance of what are referred to as assumptions. Since model checking is usually also employed in the framework of formal verification of the error-free control, these assumptions are usually already present and can be re-employed in the framework of this analysis.

The assumptions describe how the positions of the lift-off turntable HD and the presence of a workpiece WS can vary dependent on the motion direction and the current position. The below assumption

('table.vmov' = stop / \ 'table.vpos' = x0) / \

x('table.vpos' = x0) presents that the vertical position is x0 in the next status when the vertical motion has stopped and the current vertical position down is (x0). This assumption is based on the situation that the positions do not change when no motion occurs.

Possible assumptions, i.e. conditions, for the above-described control FS are described below:

process:=g (((‘table.vmov’ = stop / \ ‘table.vpos’ = x0) / \
/ \ x (‘table.vpos’ = x0) \ / (‘table.vmov’ = stop /\
/ \ ‘table.vpos’ = x1) / \ x (‘table.vpos’ = x1)
\ / (‘table.vmov’ = stop / \ ‘table.vpos’ = x2) / \
/ \ x(‘table.vpos’ = x2)
\ / (‘table.vmov’ = plus / \ ‘table.vpos’ = x0) / \
/ \ x (‘table.vpos’ = x0 \ / ‘table.vpos’ = x1) \ /
\ / (‘table.vmov’ = plus / \ ‘table.vpos’ = x1) / \
/ \ x (‘table.vpos’ = x1 / \ ‘table.vpos’ = x2) \ /
\ / (‘table.vmov’ = plus / \ ‘table.vpos’ = x2) / \
/ \ x(‘table.vpos’ = x2) \ \ (‘table.vmov’ = minus / \
/ \ ‘table.vpos’ = x0) / \ x(‘table.vpos’ = x0) \ /
\ / (‘table.vmov’ = minus / \ ‘table.vpos’ = x1) / \
/ \ x (‘table.vpos’ = x0 \ / ‘table.vpos’ = x1) \ /
\ / (‘table.vmov’ = minus / \ ‘table.vpos’ = x2) / \
/ \ x(‘table.vpos’ = x1 \ / ‘table.vpos’ = x2)) / \
/ \ ((‘table.hmov’ = stop / \ ‘table.hpos’ = x0) / \
/ \ x(‘table.hpos’ = x0) \ / (‘table.hmov’ = stop / \
/ \ ‘table.hpos’ = x1) / \ x(‘table.hpos’ = x1) \ /
\ / (‘table.hmov’ = stop / \ ‘table.hpos’ = x2) / \
/ \ x(‘table.hpos’ = x2) \ / (‘table.hmov’ = plus / \
/ \ ‘table.hpos’ = x0) / \ x(‘table.hpos’ = x0 \ /
\ / ‘table.hpos’ = x1) \ / (‘table.hmov’ = plus
/ \ ‘table.hpos’ = x1) / \ x(‘table.hpos’ = x1 \ /
\ / ‘table.hpos’ = x2) \ / (‘table.hmov’ = plus / \
/ \ ‘table.hpos’ = x2) / \ x(‘table.hpos’ = x2) \ /
\ / (‘table.hmov’ = minus / \ ‘table.hpos’ = x0) / \
/ \ x(‘table.hpos’ = x0) \ / (‘table.hmov’ = minus / \
/ \ ‘table.hpos’ = x1) / \ x(‘table.hpos’ = x0 \ /

```
\ / ‘table.hpos’ = x1) \ / (‘table.hmov’ = minus / \
/ \ ‘table.hpos’ = x2) / \ x (‘table.hpos’ = x1 \ /
\ / ‘table.hpos’ = x2)) / \ ( (‘table.vpos’ = x0 / \
/ \ ‘table.hpos’ = x0 / \ ‘table.vmov’ = stop / \
/ \ ‘table.hmov’ = stop / \
/ \ ‘table.part_on_table’ = no / \
/ \ x(‘table.part__on__table’ = yes) ) / \
\ / (‘table.vpos’ = x2 / \ ‘table.hpos’ = x2 / \
/ \ ‘table.vmov’ = stop / \ ‘table.hmov’ = stop / \
/ \ ‘table.part_on__table’ = yes / \
/ \ x(‘table.part__on__table’ = no) ) \ /
\ / (‘table.part__on__table’ = yes / \
/ \ x (‘table.part_on__table’ = yes) ) \ /
\ / (‘table.part_on__table’ = no / \
/ \ x(‘table.part__on__table’ = no) ) ) ).
```

Figure 8 shows a status space ZR of the lift-off turntable HD and the motion of the error-free lift-off turntable HD in the status space ZR, as derives after the implementation of the model checking on the status-finite description of the error-free control FS with the indicated assumptions.

The rows respectively show a value pair for the triad of the variables (vpos, hpos, part__on__table). A value pair for the dyad of the variables (vmov, hmov) with the respective, above-defined value sets is respectively shown in the columns.

Shaded circles in the status space ZR mark “forbidden” or, respectively, “dangerous” conditions in view of the safety condition. Bold-face circles in the status space ZR mark statuses that the lift-off turntable HD can assume according to the above description. These were determined by the model checking. Status transitions in the status space ZR are indicated with arrows.

Figure 9 shows the status space ZR of the lift-off table HD and the movement of the lift-off turntable HD in the status space ZR when the sensor "part___on___table" incorrectly reports a workpiece WS. The same designations are employed in Figure 9 as in Figure 8. It can be clearly seen that statuses can occur for this error case that cannot be achieved in the error-free system. These statuses are referenced VZ in Figure 9.

Failure probabilities that respectively describe the probability for the occurrence of an error at the sensor x or, respectively, actuator y are allocated to the individual sensors x and/or actuators y. By linking compound probabilities for the occurrence of errors of various sensors and/or actuators and for the occurrence of various statuses, a very simple risk estimate for the technical system can ensue on the basis of this procedure. Details for calculating dependent probabilities in error [...] may be found in [1].

The error analysis thus ensues taking the failure probabilities into consideration.

The method is preferably implemented for all possible errors of the existing sensors and/or actuators.

The following publications were cited in the framework of this document:

[1] DIN 25424, Part 1: Fehlerbaumanalyse: Methode und Bildzeichen; Part 2: Handrechenverfahren zur Auswertung eines Fehlerebaums

[2] J. Dekleer und B. C. Williams, Diagnosing Multiple Faults, , Elsevier Science Publishers, Artificial Intelligence, Vol. 32, 1987, pp. 97-130

[3] K. Nökel, K. Winkelmann, Controller Synthesis and Verification: A Case Study, in: C. Leverentz, T. Lindner, Formal Development of Reactive Systems, Lecture Notes in Computer Science (No. 891), Springer 1995, pp. 55-74

[4] J. Burch et al, Symbolic Model Checking for Sequential Circuit Verification, IEEE Trans. On Computer-Aided Design of Integrated Circuits and Systems, Vol. 13, No. 4, pp. 401-424, April 1994.

[5] R. Bryant, Symbolic Boolean Manipulation with Ordered Binary-Decision Diagrams, ACM Computing Survey, Vol. 24, No. 3, pp. 293-318, September 1992.

PATENT CLAIMS

1. Method for computer-supported error analysis of sensors and/or actuators in a technical system that is present in the form of a status-finite description that exhibits statuses of the technical system, using a computer.

a) whereby a status-finite description of the technical system is determined for the error case for an error of a sensor and/or of an actuator;

b) whereby a first set of achievable statuses is determined for the technical system;

c) whereby a second set of achievable statuses is determined for the error-effected technical system;

d) whereby a difference set is formed from the first set and the second set;

e) whereby result conditions are determined from the difference set, these meeting prescribable conditions.

2. Method according to claim 1, whereby method steps a) through f) are implemented for all possible errors of sensors and/or actuators that the technical system comprises.

3. Method according to claim 1 or 2, whereby failure probabilities are allocated to the sensors and/or actuators; and whereby the error analysis ensues taking the failure probabilities into consideration.

4. Method according to one of the claims 1 through 3, whereby method steps b) and c) ensues [sic] according to the method of model checking.

5. Method according to one of the claims 1 through 4, whereby a status-finite description of a process implemented by the technical system is taken into consideration in the method.

6. Method according to one of the claims 1 through 5, whereby the status-finite description is realized by a finite automat.

7. Method according to claim 6, whereby the status-finite is realized by a finite automat in the form of a binary decision diagram (BDD).

8. Employment of the method according to one of the claims 1 through 7 in rapid prototyping of the technical system.

9. Employment of the method according to one of the claims 1 through 7 in the framework of error diagnosis of the technical system.

10. Employment of the method according to one of the claims 1 through 7 for generating critical test cases for a commissioning and a system test of the technical system.

11. Employment of the method according to one of the claims 1 through 7 for preventive maintenance of the technical system.

ABSTRACT

Method For Computer-supported Error Analysis of Sensors And/or Actuators in a Technical System

A method is proposed wherein a status-finite description of the technical system is determined for the error case for an error of a sensor and/or of an actuator, and a status-finite description of the technical system is determined for the error-free case. The achievable statuses are preferably determined with model checking for both descriptions. A difference set of statuses of the two descriptions is formed, a check being carried out for the statuses thereof to see whether these statuses meet prescribable conditions (for example, safety conditions).

FIG 1

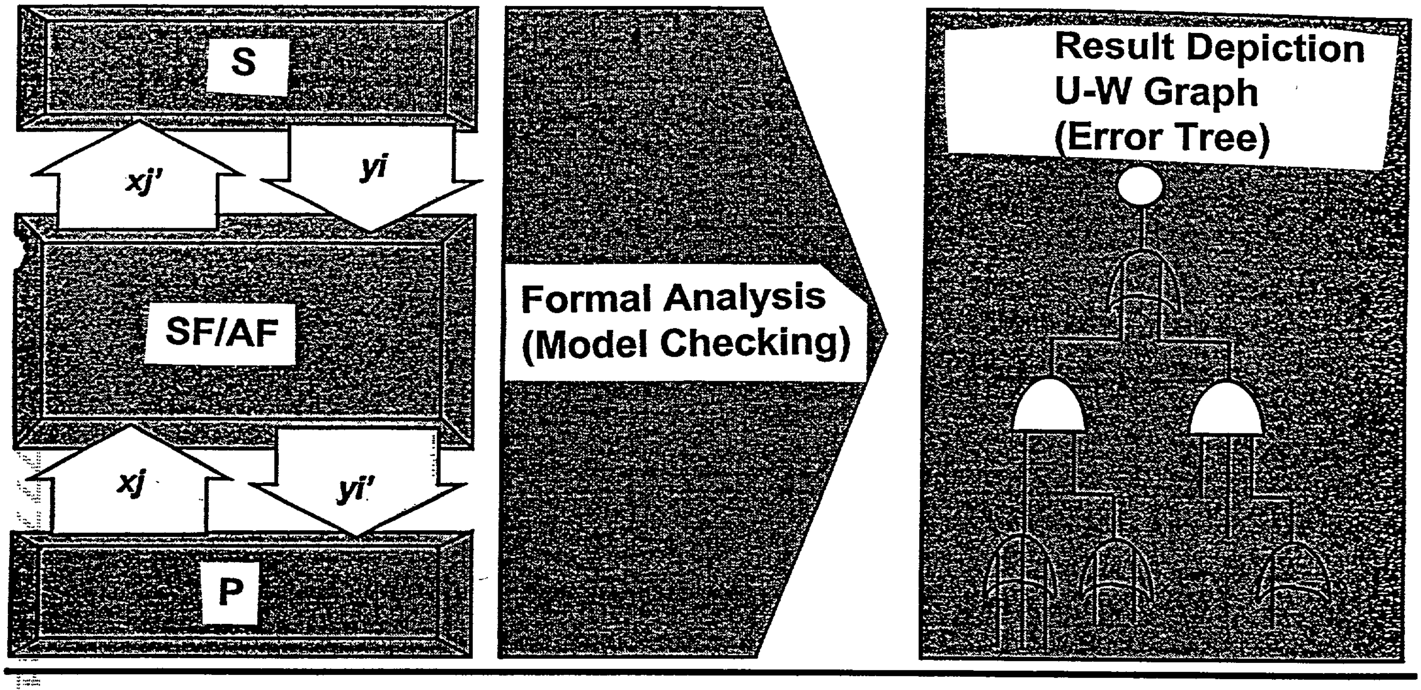
S
xj'
yi
SF/AF
xj
yi'
P
Formal Analysis
(Model Checking)
Result Depiction
U-W Graph
(Error Tree)

FIG 2

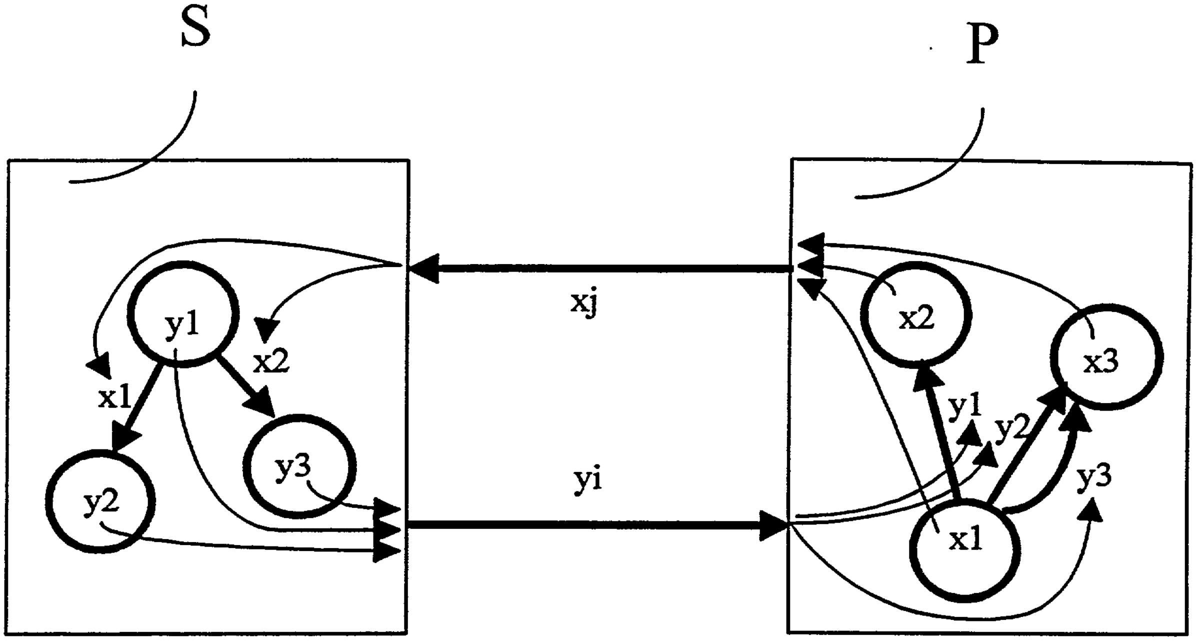

FIG 3

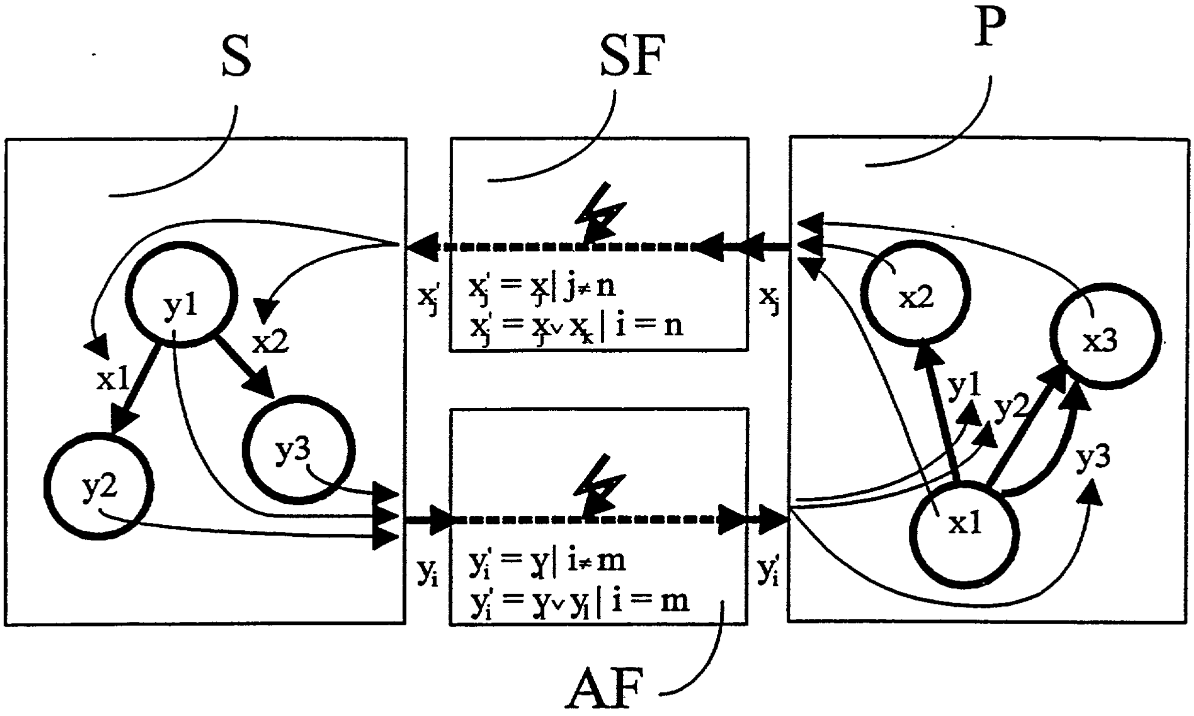
S
SF
P
y1
x1
x2
y2
y3
x_j'
$x_j' = x_j | j \neq n$
$x_j' = x_j \vee x_k | i = n$
x_j
x2
x3
y1
y2
y3
x1
y_i
$y_i' = y_i | i \neq m$
$y_i' = y_i \vee y_l | i = m$
y_i'
AF

FIG 4

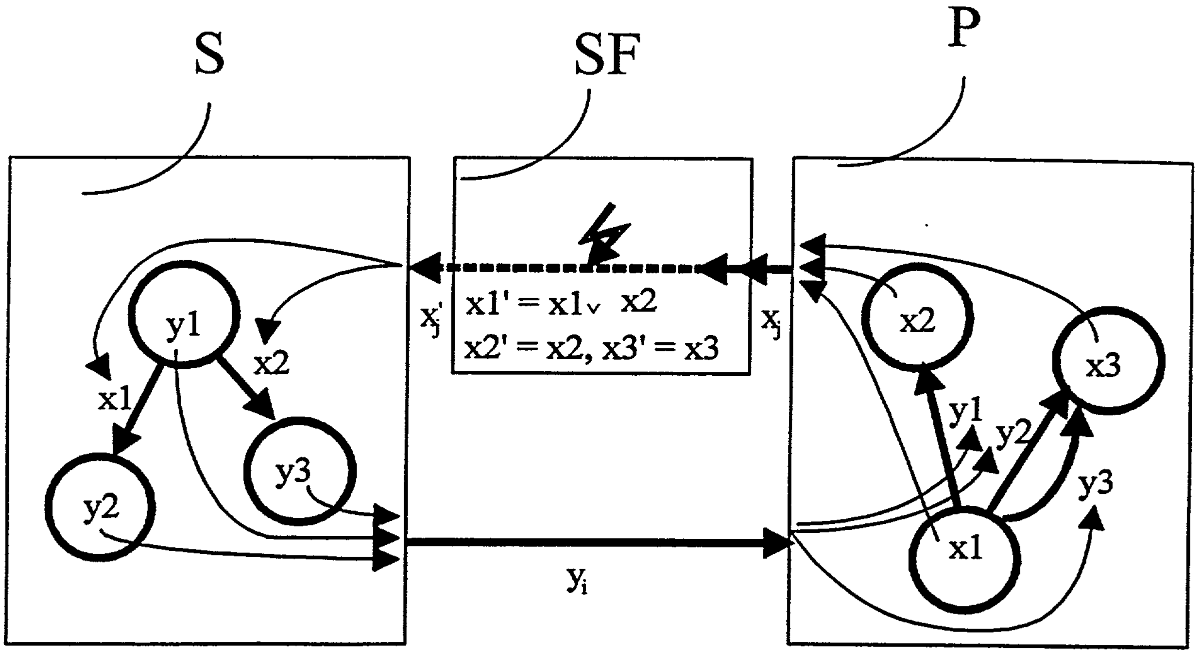

FIG 5

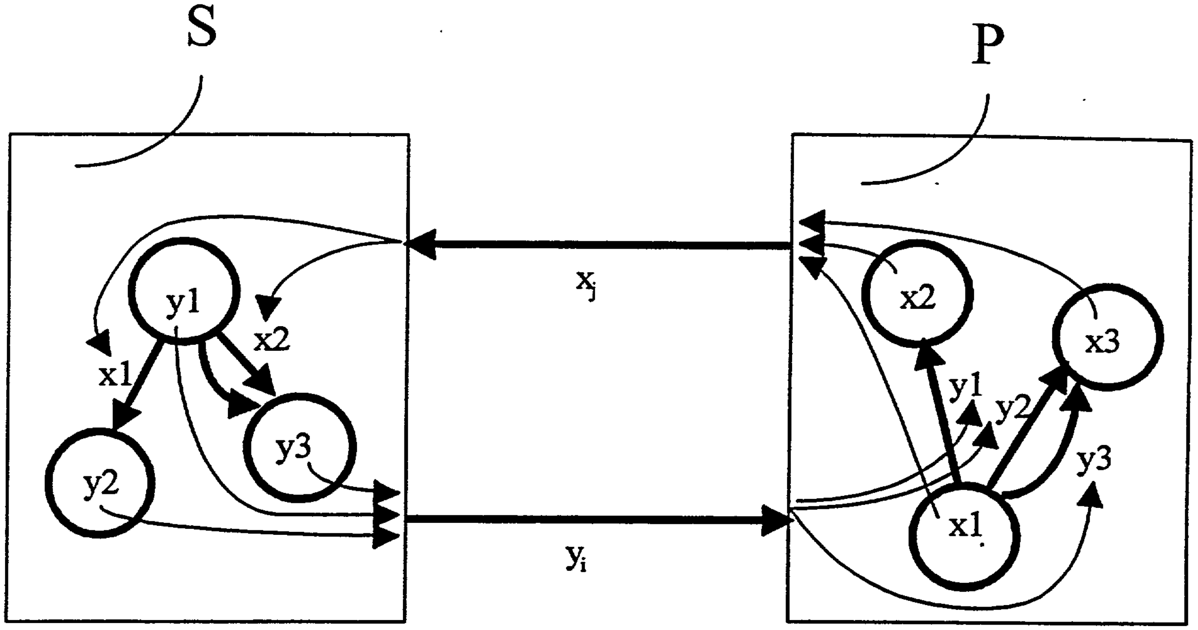

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FIG 6

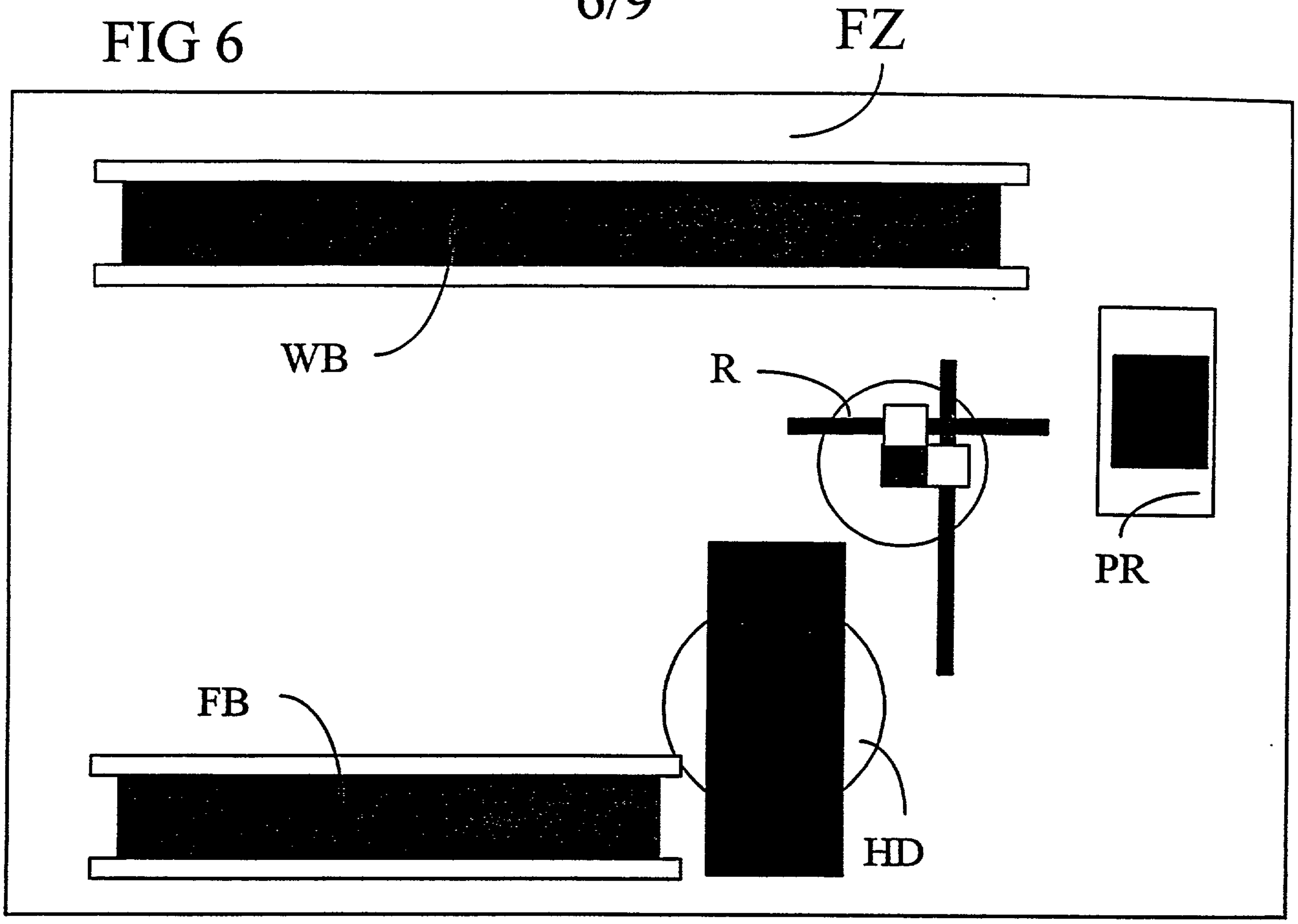

FIG 7

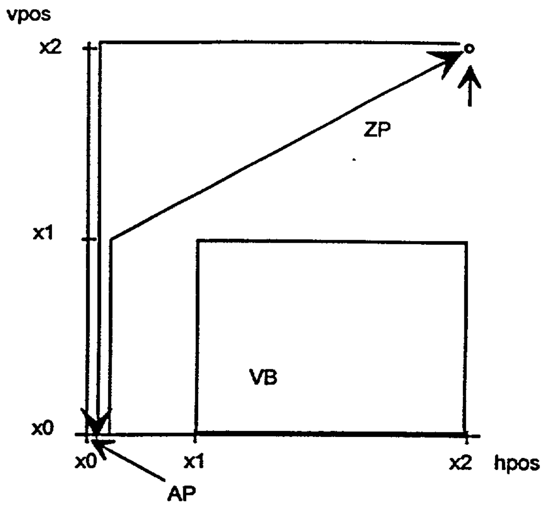

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FIG 8

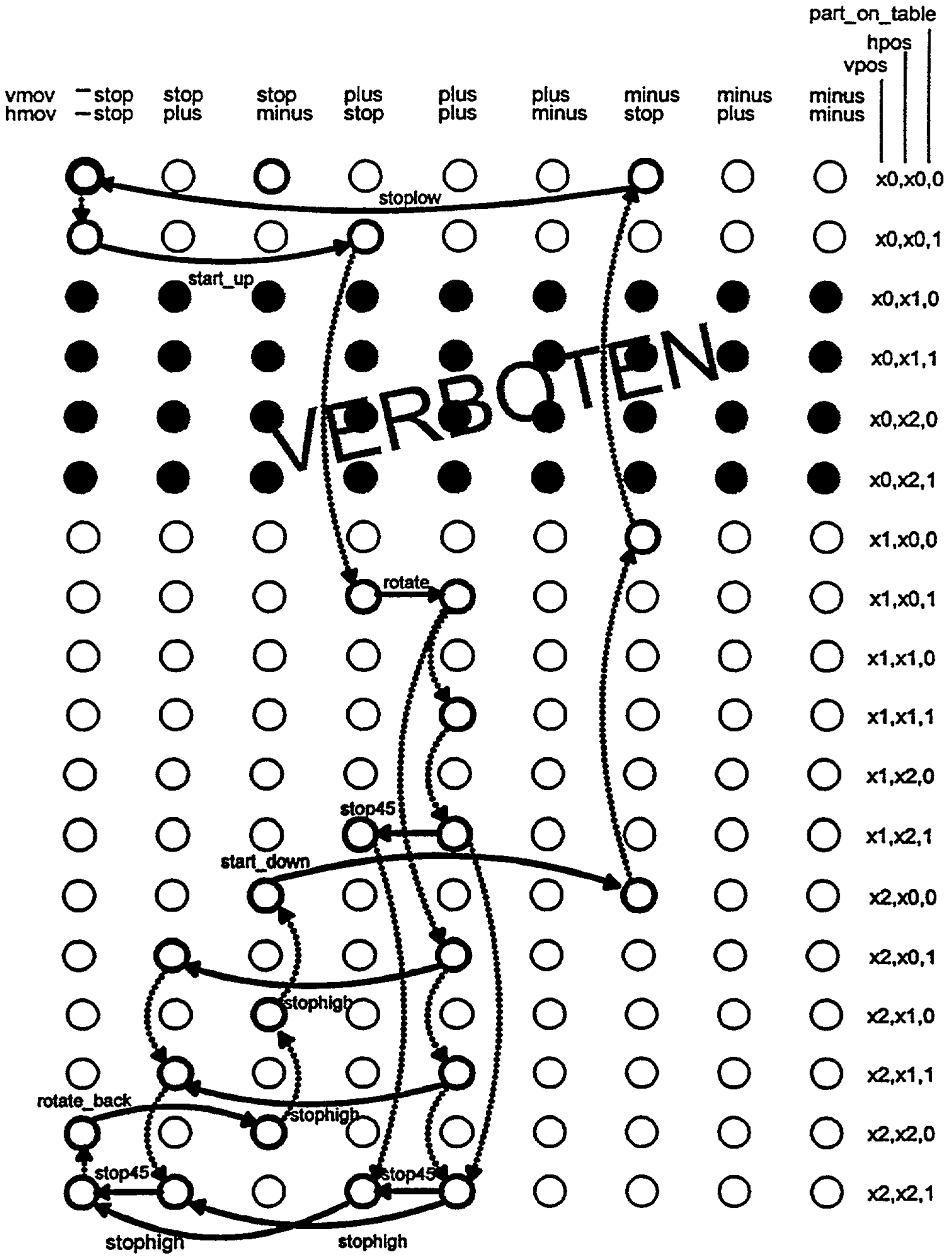
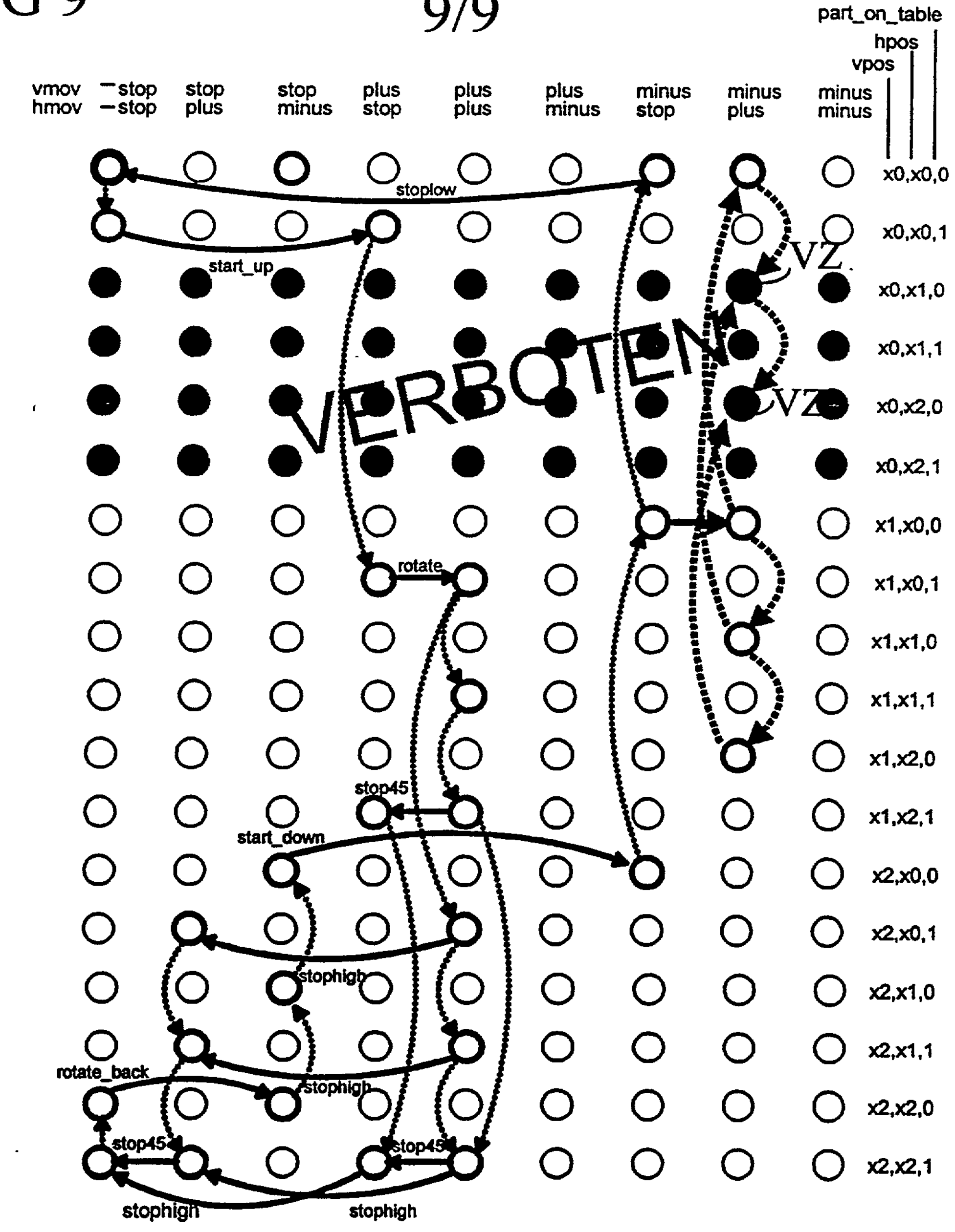


FIG 9


part_on_table
hpos
vpos
vmov
hmov
stop
stop
stop
plus
stop
minus
plus
stop
plus
plus
plus
minus
minus
stop
minus
plus
minus
minus
x0,x0,0
x0,x0,1
x0,x1,0
x0,x1,1
x0,x2,0
x0,x2,1
x1,x0,0
x1,x0,1
x1,x1,0
x1,x1,1
x1,x2,0
x1,x2,1
x2,x0,0
x2,x0,1
x2,x1,0
x2,x1,1
x2,x2,0
x2,x2,1
stoplow
start_up
VERBOTEN
VZ
VZ
rotate
stop45
start_down
stophigh
stophigh
rotate_back
stop45
stop45
stophigh
stophigh

Declaration and Power of Attorney for Patent Application
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German Language Declaration

Als nachstehend benannter Erfinder erkläre ich hiermit an Eides Statt:

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Verfahren zur rechnergestützten Fehleranalyse von Sensoren und/oder Aktoren in einem technischen System

deren Beschreibung

(zutreffendes ankreuzen)

☒ hier beigefügt ist.

☐ am ____________________ als
PCT internationale Anmeldung
PCT Anmeldungsnummer ____________________
eingereicht wurde und am ____________________
abgeändert wurde (falls tatsächlich abgeändert).

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My residence, post office address and citizenship are as stated below next to my name,

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

____
____
____

the specification of which

(check one)

☐ is attached hereto.

☐ was filed on ____________________ as
PCT international application
PCT Application No. ____________________
and was amended on ____________________
(if applicable)

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I hereby claim foreign priority benefits under Title 35, United States Code, §119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

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Prior foreign appplications
Priorität beansprucht

Priority Claimed

197 09 956.4	Germany	11. März 1997	☒	□
(Number) (Nummer)	(Country) (Land)	(Day Month Year Filed) (Tag Monat Jahr eingereicht)	Yes Ja	No Nein
			□	□
(Number) (Nummer)	(Country) (Land)	(Day Month Year Filed) (Tag Monat Jahr eingereicht)	Yes Ja	No Nein
			□	□
(Number) (Nummer)	(Country) (Land)	(Day Month Year Filed) (Tag Monat Jahr eingereicht)	Yes Ja	No Nein

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(Application Serial No.) (Anmeldeseriennummer)	(Filing Date) (Anmeldedatum)	(Status) (patentiert, anhängig, aufgegeben)	(Status) (patented, pending, abandoned)
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German Language Declaration

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POWER OF ATTORNEY: As a named inventor, I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith. *(list name and registration number)*

(19)

And I hereby appoint

Messrs. John D. Simpson (Registration No. 19,842) Lewis T. Steadman (17,074), William C. Stueber (16,453), P. Phillips Connor (19,259), Dennis A. Gross (24,410), Marvin Moody (16,549), Steven H. Noll (28,982), Brett A. Valiquet (27,841), Thomas I. Ross (29,275), Kevin W. Guynn (29,927), Edward A. Lehmann (22,312), James D. Hobart (24,149), Robert M. Barrett (30,142), James Van Santen (16,584), J. Arthur Gross (13,615), Richard J. Schwarz (13,472) and Melvin A. Robinson (31,870), David R. Metzger (32,919), John R. Garrett (27,888) all members of the firm of Hill, Steadman & Simpson, A Professional Corporation.

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85th Floor Sears Tower, Chicago, Illinois 60606

1-00

Voller Name des einzigen oder ursprünglichen Erfinders: LIGGESMEYER, Peter	Full name of sole or first inventor:
Unterschrift des Erfinders Datum Peter Liggesmeyer 27.02.98	Inventor's signature Date
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Staatsangehörigkeit Bundesrepublik Deutschland	Citizenship
Postanschrift Hauptstr. 89	Post Office Address
D-85579 Neubiberg Bundesrepublik Deutschland	
Voller Name des zweiten Miterfinders (falls zutreffend):	Full name of second joint inventor, if any:
Unterschrift des Erfinders Datum	Second Inventor's signature Date
Wohnsitz	Residence
Staatsangehörigkeit	Citizenship
Postanschrift	Post Office Address

(Bitte entsprechende Informationen und Unterschriften im Falle von dritten und weiteren Miterfindern angeben).

(Supply similar information and signature for third and subsequent joint inventors).